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14. ABSTRACT

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Oil on the water characterization with coherent fringe projection and digital holographic in-line interferometry

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Abstract: We combine optical methods for sensing of oil films. These are: coherent fringe projection (CFP), digital holographic in-line interferometry (DHILI). The methods of CFP and DHILI are described as coherent superposition of partial interference patterns

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1. Introduction

Although there are several methods of remote detection/identification of crude oil in water and/or on the solid surfaces, there is still a need for more efficient and reliable methods [1]. Spectroscopic methods allow characterization of oil composition [2] but give little information about spatial distribution of oil. Digital holographic in-line interferometry (DHILI) allows determination oil film thickness [3,4] and size of oil droplets, but requires elaborate image processing. Coherent fringe projection (CFP) techniques proved to be efficient in non-contact metrology of microstructured objects [5]. We suggest combining DHILI and CFP in one set-up for improved detection/identification of oil. We propose a unified approach for modeling of both DHILI and CFP that is suitable for remote characterization of oil films (spills) in sea water.

2. Experiments for remote determination of oil droplets and films

The methodology and experimental setup method for determining the size of the droplets of oil on the water surface is based on illumination of the oil/water surface by an interference pattern with known period d. Figure 1 shows the experimental setup, which uses a DPSS laser with wavelength $\lambda = 532$ nm. The plane-wave laser beam with diameter 24 mm (1, Figure 1) illuminates glass plate (with wedge angle 1,2 ″) with a semi-transparent back plane. As a result, the interference pattern of reflected signals from the front and back surfaces of the plates with period d = 3 mm illuminates the analyzed object (3). Since the glass plate is illuminated by the plane-wave beam, the reflected beams are also plane waves, and its period of interference pattern does not change with distance.

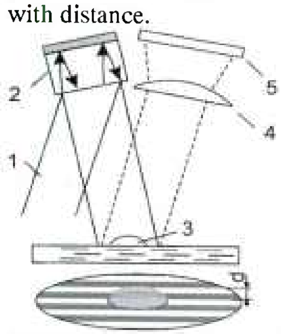

Figure1. Depicts the experimental set up: 1) Plane-parallel laser beam, 2) Wedged glass plate 3) Object, 4) Lens, 5) Screen

When the droplet of oil spreads on the water surface, there is interference over the entire surface of the object (Figure 2). Interference rings are the result of interference between the reflected beam from the front surface of the oil droplet and a plane wave reflected from the water surface.

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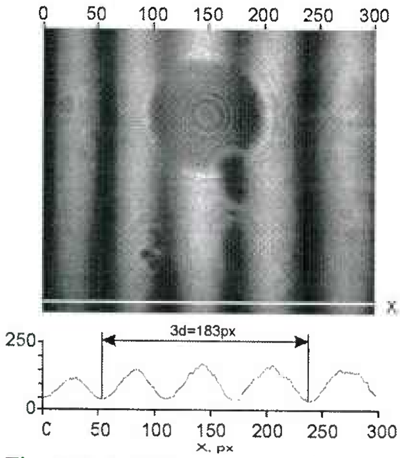


Figure.2. Interference pattern of the drop of motor oil

The image was processed by a graphical editor to determine the pixel-by-pixel distribution of the grey scale along the frame. A one-pixel-thick line (white line X, Figure 2) was chosen and scanned perpendicularly to the interference pattern along the entire image (total of 300 pixels). Fig.2 shows the pixels brightness distribution (from 0 to 255 of the grey scale) where the alternation of maxima and minima corresponds to the a priori known fringe pattern period d=3 mm. By dividing the value of the d=3 mm period by the number of pixels between the maxima (or minima), we found that 1 mm of the real object dimension corresponds to ~20 pixels of the image. This allows determination of the dimensions of motor oil drop at pixel by pixel scanning of the object in graphical editor..

3.Theory of the stripe and circular fringes formation

We will consider the interference pattern on the screen, formed by the two near-parallel waves reflected from the oil-water surface. Complex amplitude of these two fields can be written as:

$$S_l = (R_l + R_{ld}) S_{l0} \exp(-ik_l x) \quad (1)$$

Here the reflection coefficients from water (***R_l***) and oil spot (***R_{ld}***) and input amplitudes (***S_{lo}***) can be presented in the form

$$R_l = r_l \exp(i\varphi_l), R_{ld} = r_{ld} \exp(i\varphi_{ld}), S_{l0} = \sqrt{I_{l0}} \exp(i\varphi_{l0})$$

where subscript l =1,2 , k_l is the x-component of the wave vector, x is a coordinate perpendicular to the lines of the fringe pattern. For near collinear propagation of two beams, we assume that the reflection coefficients for two beams are equal ($r_1 = r_2 = r$, $r_{1d} = r_{2d} = r_d$) , so the pattern on the screen may be presented as

$$I = |S_1 + S_2|^2 = I_0 (r + r_d)(1 + m\cos(\varphi) + M\cos(\phi) +$$
$$0.5mM(\cos(\phi + \varphi) + \cos(\phi - \varphi))) \quad (2)$$

Here I_0 is input intensity , and phases are

$$\phi = \phi_0 + 2\pi x / d, \varphi = \varphi_0 + (\varphi_l - \varphi_{ld})$$

zero indexes means, that possible constant phase shift may be introduced during reflection from the surface. From Eq.(3) it can be seen that ϕ is phase difference between plane (reflected from the unperturbed water) waves that forms partial interference fringe patten with contrast ***M***, while φ is phase diference in the partial interference pattern (with contrast m) formed by the plane wave and the wave diffracted from the oil spot. We will model oil film convex-type shape on the water surface as a product of two shapes :1) segment of sphere with curvature radius ***R*** that looks from above as a plano-convex lens with radius ***P*** and height h (sagitta), and 2) step-like function F. This model of oil thickness changes **Z** (as measured from the water level) can be written as:

$$Z(x,y) = \left(\frac{1}{2R}\right)(P^2 - x^2 - y^2)(1 - \exp[\frac{b}{R^2}\{P^2 - x^2 - y^2\}])^{-1} \quad (3)$$

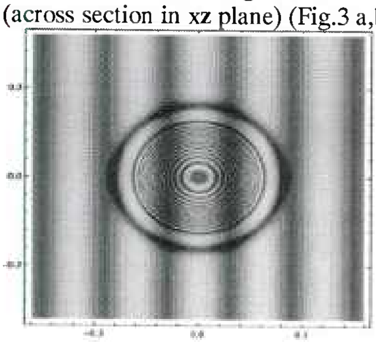
This shape of the oil film was dictated by an effort to simulate the experimental profile of the oil film. In this simulation parameter b is chosen as a big number (in the order of 10^5 - 10^6) in an effort to best fit the experimental

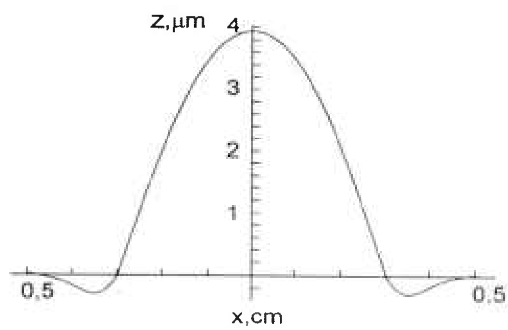
shape of the boundary of the oil film on the water. The relation of phase modultion $\varphi(x,y,z)$ introduced by the oil film can be found from the general expression, known in inferferometry of reflective surfaces

$$\varphi(x,y,z)=(\frac{2\pi}{\lambda})(\vec{n}\vec{S})=\frac{4\pi}{\lambda}Z(x,y)\cos(\theta) \quad (4)$$

here $\vec{n}$ is the unit vector of the surface deformation, $\vec{S}$ is the so-called sensitivity vector, equal to the difference between reflected and incident wave vectors, θ is the angle of incidence (measured from the z-axis).

The experimental interference pattern of the oil-on water spot on the screen (Fig. 2) is compared with the theoretical one. Choosing a set of parameters ***P***= 0.369 cm, ***L***= 0.7cm, λ= 532 nm, ***R*** = 170 cm, ***M*** = ***m*** = 0.5, ***b***= 8.5 10^5, $\varphi_0=\phi_0=0$ we will get the density plot of intensity on the screen and plot the modelled shape of the oil film (across section in xz plane) (Fig.3 a,b).





a) b)

Figure 3. a) Calculated density plot of the combined intensity pattern on the screen; b) **XZ** cross section of the modeled surface profile of the oil spot. For parameters best fitted experimental density plot (m= M=0.5, P= 0.3369 cm, L=0.7cm, R =170cm, b = 8.5 10^5 and assuming no constant phase shift during reflection).

4. Comparison of experimental results with theoretical modeling.

In the presented approach for deciphering of the interference pattern from the oil spots, we used a method of probed shapes by modeling oil spot surface profile with functions, according to symmetry of spot (in our case by convolution of part of sphere with a step-function with several adjusted parameters). Some of parameters, like stripe fringe period ***d***, contrasts of partial interferograms ***m*** and ***M*** , circular symmetry are estimated and deduced from the experimental results. By varying the two remaining adjusted parameters (curvature radius ***R*** and parameter ***b*** of step-function), we achived a best-fitting comparison between experimental and theoretical desity plots. This fitting allow us to find maximal heigth (sagitta) of the modeled shape of the oil circular spot.

Our approach of choosing probed function for the oil spot surface with parameters, defined by best-fitting comparison with experiment may work well for the shapes allowing modeling with analytical functions (like circular, elliptical and similar shapes).

In our case of cylindical symmetry oil film shape is defined by two parameters: radius of spot ***P*** and sagitta (height ***h***). From fringe projection pattern radius a was determined as ***P*** = .3 cm, from fittng densiy plots oil film maximal thickness ***h*** (sagitta) was estimated as ***h*** = 0.375 microns (see Fig.3).

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